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Natural Uranium Heavy-Water Moderated Organic-Cooled Power Converter Reactor

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Introduction

To provide a more effective use of natural uranium in nuclear power secondary fuel-plutonium must be introduced in uranium fuel cycle. Plutonium can considerably increase the utilization factor of U^{238} in thermal neutron reactors and practically ensure a complete use of U^{238} in fast breeders. Therefore one of the main purposes of employing uranium reactors, along with power generation, is production of plutonium.

The main features of uranium converter reactors (besides their efficiency) are:

1. Uranium utilizing effectiveness i.e. the amount of electric energy and plutonium, produced when reprocessing 1 ton of natural uranium.

2. Plutonium fabrication effectiveness, i.e. per unit of time per unit of reactor power.

The promising type of converter reactors in our opinion are natural uranium heavy-water moderated reactors. By the effectiveness of utilizing uranium, reactors of this type have an advantage over all the existing thermal converter reactors. They have a lower effectiteness of plutonium fabrication as compared only with fast converter reactors.

One of the possible variants of a heavy-water reactor is an organic-cooled reactor. Organic liquids do not react with uranium, which considerably increases the reactor operation safety, thus permitting the application of such

reactor not only for atomic power stations but also for heating installations located near populated areas. The coolant circuit can be manufactured of conventional structural materials. Besides, comparatively high thermal parameters of organic coolants are obtained at a low pressure, which facilitates the solution of a number of technological problems, when constructing large 500-1000 $MW_{(b)}$ plants. The latter fact is of not minor importance as the power of the plant considerably effects both the capital investiments and the cost of generated electric energy.

In this respect an organic-cooled reactor is a step forward as compared with high-pressure vessel reactors, in which the power is limited by technologically realised dimensions of the pressure vessel.

The present report deals with the description and comparison of two different natural uranium heavy-water moderated organic cooled reactors. The thermal and physical properties as well as radiation and thermal resistance of this liquid, obtained by hydraulic purification of polyalkilbenzol resin fraction (wastes of cumene production) are not lower than those of such a wellknown coolant as monopropyldiphenyl but it is considerably cheaper. The main difference between the two reactors, presented in the report, consists in the fact that one reactor (R-1) possesses an increased plutonium fabrication effectiveness, and the other (R-2) effectively utilizes uranium.

The possibility of constructing similar reactors with different characteristics depends on the specific features of plutonium production in natural uranium thermal reactors. As it is shown in Fig.1 approximately 2/3 of plutonium (Pu^{239} + Pu^{241}) are produced with a fuel burnout of 3000 MWd/t . Therefore, e.g. a reactor with a burnup of ~ 3000 MWd/t can produce two times as much plutonium as a reactor with a burnup of ~ 9000 MWd/t at the same reactor power.

Given below is the description of the design and characteristics of R-I and R-2 reactors.

Description of Reactor R-I

The development of the reactor design (Fig.2) was based on the following:

a) vertical postion of the reactor axis;

b) fabrication of the reactor core from separate easily replaceable fuel channels isolated from the moderator;

c) upward direction of the coolant flow into the reactor core;

d) fuel elements made in the form of small slugs.

The reactor consists of a number of tanks: a pressure chamber, a core tank, a shield tank and a dump tank, which are pierced by fuel channels and control and safety elements channels. Despite large dimensions of the reactor its design permits manufacturing it from separate fully adjusted and tested at the Manufacturing plant with welding works during assembly reduced to a minimum, to prevent the misalignment of the holes in the reactor structural assemblies.

The height of the reactor assembled is 25 m.

Pressure chamber is designed for the distribution of the coolant among the fuel channels, reception of spent fuel elements discharged from the channels and their transfer into the hydraulic transportation system, made similar to hydraulic transportation systems. The pressure chamber is a carbon steel structure consisting of an upper flat truss-type plate 7500 mm dia. with holes to receive fuel channels shanks. Welded to the plate through a shroud is a cone, ended in a shroud with pipes for the coolant inlet pipelines. The pressure chamber is provided with an inner cone the lower part of which is fitted with a nozzle for hydraulic transportation of fuel elements.

Core tank - is manufactured from an aluminium alloy. The tank diameter is 7000 mm, the height is 5000 mm. The tank has a flat cover and a bottom flared in which are calandria-type pipes for the passage of fuel channels. The tank is filled with a moderator - heavy water. Above the moderator level is a gas cavity intended for blowing off the oxyhydrogen gas.

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Provision is made for checking the moderator level and a possible leakage from it with the tightness of the calandria-type pipes affected. The core tank is installed on the upper plate of the pressure chamber.

Upper shield tank - is a cylinder 7500 mm dia. and 4000 mm high, with a flat bottom flared in which aligned with calandria-type pipes of the core tank, the pipelines to pass the fuel channels and the jackets for the control and safety elements channels. The tank cavity is filled with organic liquid (the same as the coolant) with a temperature of 90°C which serves for the protection of the reactor top section.

The tank rests on the biological shielding annular water tank. The shielding tank level is ventilated for removing the gaseous products resulting from the organic liquid radiolysis. The tank is made of an aluminium alloy.

Dumps tank serves for collecting a hot coolant which leaks from the fuel channel holes and for distributing it among into the steam generators circulation pipelines. Located above the coolant level is a gas blanket to blow off and remove the gaseous products resulting from the coolant radiolysis. The tank upper cover is also used as the reactor upper plate, on which the fuel channel heads and the temperature sensing element are secured and the cables, wires and pulse lines are laid. The tank is made of a carbon steel. The dump tank rests on the shielding water tank.

Fuel channels (Fig.3) are designed for housing the fuel elements and for passing the coolant flow through the reactor core. To flatten the neutron flux distribution according to the core diameter, the channels are made of the two types.

The channel end sections are secured in the pressure chamber in special mouth pieces and the heads - on the dump tank cover.

Although such attachment of the channel in the reactor makes it necessary to have a circuit for collecting the coolant leaks through the channel lower seal, it provides

for free thermal expansions along the channel axis, compensation of the difference in thermal expansion of individual reactor tanks along the radius and easy removal and installation of the channel. In the channel lower part is a collet which prevents an inadvertent discharging of fuel elements, in the channel upper part somewhat above the core is a collet preventing the fuel elements from floating due to pressure difference in the reactor core.

The channels are installed in the cells so that a clearance of 8 mm is formed between the calandria-type pipes of the core tank and the channel walls. The entire length of the channel is 16.5 m. The channel is provided with devices monitoring the fuel element tightness and the coolant outlet temperature.

Fuel element shown in Fig.4 is a thick-walled annular uranium core clad with a ribbed jacket made of magnesium-beryllium pseudo-alloy powder. The uranium core is produced by hot pressing from an ingot followed by machnining and hardening from β -phase.

Fuel elements manufacturing technology is checked on several experimental batches for the loop tests. The experiment showed that the laboratory technology of fuel elements production can be easily adapted to mass production.

Manufacturing of fuel elements in the form of slugs small in weight and size:

a) simplifies their manufacturing production;

b) facilitate solving the refueling problem, as it permits using a reliable hydraulic transportation system, which protects the reactor top section and the central hall from dirt.

The reactor refueling is accomplished by a special machine without reducing the reactor power. The loading and unloading operations are aligned as fuel elements, being discharged, are replaced in the reactor core with a fresh party of the same quantity of fuel elements.

The reactor main data are presented in the Table I.

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Description of Reactor R-2

As mentioned above, the reactor R-2 (Fig.5) differs from the reactor R-1 in being designed for deeper fuel burn-ups. This led to:

a) change in fuel elements which are made of uranium dioxide, placed in tubular assemblies (clusters). The length of such an assembly is 400 mm;

b) increase in the core diameter and introduction of end reflectors;

c) replacement of the tapered pressure chamber with a system of pipelines which provide an individual coolant supply to the fuel channels.

The loading and discharging of fuel elements from the channels are accomplished by means of a special fueling machine from the reactor cover.

The above mentioned called for slight changes in the fuel channel construction, principal change in the coolant supply to them and constructional changes in the entire reactor bottom.

The upper sections of the reactor from the level of the core bottom are similar in the design diagram to those of the R-1 reactor.

The materials, used for the core, fuel channel, fuel elements **Cladding** and for other assemblies of the reactor, are similar to those approved for the R-1 reactor.

R-2 reactor is a vertical-type assembly comprising the following main parts (from the bottom to the top):

1. Dump tank and lower shielding.
2. Core with heavy water end reflectors and a side graphite reflector.
3. Upper shielding.
4. Dump tank (upper).
5. Fuel channels.

This section deals with the description of the design diagrams according to steps 1 and 5; the description of the assemblies 2, 3 and 4 are given in the corresponding section of the R-1 reactor description.

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The dump tank and lower shielding consist of a shell with a flat ribbed bottom pierced with cylindrical throttles into which the ends of the fuel channels enter.

The compound steel shell is fitted with a flange supporting the core aluminium vessel.

The whole system rests on cylindrical rollers installed on the plate constructionally built in the reactor water shielding system.

Fuel channel

The fuel channel is constructionally similar to that of the R-1 reactor but differs from it in provision of more effective end reflectors:

a) In the lower reflector area the fuel channel and calandria-type pipes have a smaller diameter, on the lug, thus obtained the fuel element column is installed ;

b) From the top of the channel a rod is inserted which ends near the surface of the upper fuel element. The rod is used for: 1) holding the fuel elements in the reaction area to prevent them from coming to the surface under the action of the coolant flow; 2) forcing the coolant out of the upper reflector area with the rod lower end.

Table I

Characteristics of R-1 and R-2 reactors

No.	Name	Characteristics R-1	R-2
1	2	3	4
1	Electrical output	500 MW	500 MW
2	Heat output	1 600 MW	1600 MW
3	Coolant	Organic liquid PAB	Organic liquid PAB
	Coolant temperature:		
	at reactor inlet	230°C	230°C
	at reactor outlet	300°C	300°C
4	Moderator	heavy water	heavy water
	moderator volume in reactor	150 m^3	220 m^3
5	Reflector		
	side	graphiie 300 mm	graphite 800 mm
	end	-	upper, lower } 500 mm of heavy water
6.	Core		
	core diameter	7,000 mm	8,000 mm
	height	4,000 mm	4,000 mm
	number of fuel channels		
	a) central zone	680 ea	580 ea
	b) peripheral part	356 ea	290 ea
	Fuel channel space	square lattice 185x185 mm	square lattice 240x240 mm
	Fuel	natural metal uranium	natural U_2O
	Quantity of uranim in core	100 tons	120 tons

1	2	3	4
7	Steam generator cycle		
	a) in increased pressure step		
	Steam consumption	1570 t/hr	1570 t/hr
	Steam pressure	48 atm	48 atm
	b) second step		
	Steam consumption	1450 t/hr	1450 t/hr
	Steam pressure	27 atm	27 atm

Refueling of R-1 and R-2 reactors

The fuel is continuously loaded in the R-1 and R-2 reactors during their operation. To refuel any channel special fueling machines are used.

A continuous refueling permits increasing the fuel burnup with a fixed reactivity margin as compared to a simultaneous refueling of all the channels (which is most important for the R-2 reactor having a high burnup) and decreases the difference between the maximum and average values of the discharged fuel burnup.

Besides a continuous refueling in the R-1 reactor the fuel moves along the channel.

It is achieved by refueling in two steps - each time half a channel is filled. In this case the difference between the maximum and average values of the discharged fuel burnup equals to ~ 10% which is important in case metallic uranium is used. The distortion of the neutron field along the channels, in this case , is insignificant but even it can be eliminated by introducing in the upper section of the core the regulators which permit passing the "Xenon peak poisoning" after a short shut-down of the reactor.

For choosing the method of refueling the R-2 reactor channels, the effect of various methods of refueling on the form of the thermal neutron flux distribution along the channels and on the burnup with a fixed reactivity margin has been studied.

The results obtained are given in Table II.

After studying the methods of refueling the R-2 reactor channels, given in Table No.2, we have chosen method No.2 consisting in simultaneous complete refueling of the channel. This method permits obtaining the burnup only 7% lower than that achieved in case of a continuous refueling (method No.3) but it is technologically simpler.

Method No.2 can be realized in vertical-type reactors.

The use of a R-1 reactor method of refueling in the R-2 reactor (method No.4) is unnecessary due to a considerable distortion of the thermal neutron field. Besides, discharge of the fuel down and transportation of cluster-type fuel elements are technologically difficult to realize.

Table II

Relative fuel burnup and average-to-maximum thermal neutron flux ratio (with reactivity margin of 6%) when refueling channels by various methods

Nos.	Method of refueling channels	Relative fuel burnup	Average thermal neutron flux (along channels) -to-maximum flux ratio	Max.burn-up - to average burnup ratio in fuel discharged from channels
1	Simultaneous complete refueling of a channel (reactor without end reflectors)	1.00	0.74	1.35
2	Simultaneous complete refueling of a channel (reactor with an end reflector; decrease in core height by 15%)	1.14	0.84	1.19
3	Continuous refueling . In adjacent channels			

	fuel moves in counter directions	1.22	0.56	1.00
4	Continuous refueling. In all channels fuel moves in the same direction	1.08	0.43	1.00

Experimentsl works

To prove the correctness of the constructional and design calculations a number of experiments were performed. The laboratory technology of manufacturing fuel elements was developed and experimental batches of fuel elements were produced. The interaction of a coolant with structural materials was studied. Experiments on testing the loop of the simplified model fuel channel in the reactor were carried to check the proper canning of the fuel elements included in the experimental batch, pyrolytic and radiolytic resistance of monoisopropyldiphenyl, and the velocities of polymers formation and a gas phase were determined.

Comparative experiments of irradiating in the reactor ampoules filled with monoisopropyldiphenyl and PAB coolant at the operating temperatures showed the radiolytic resistance of the PAB is not below that of monoisopropyldiphenyl. All the thermal and physical characteristics of organic coolant required for calculations were measured.

Studied was heat transfer of smooth and ribbed pipelines to the organic coolant. Critical loads versus subcooling and coolant velocity were estimated. Measured was the microstructure of neutron flux in a cell, in uranium included.

Experiments were carried out to check the serviceability of individual structural assemblies e.g. throttle sealing, lower collet, remote replacibility of the calandria-type pipe.

Utilization of plutonium in heavy-water reactor

Heavy-water converter reactors can be used without any structural modifications as purely power reactors operating in a uranium-plutonium cycle with secondary fuel.

For instance, if plutonium and uranium-138 are used as a fuel (free from uranium-235) only 25% of fission fragments of the discharged fuel are obtained due to fission of plutonium present in the charged fuel. 75% of fragments are obtained due to a fission of plutonium produced in the reactor.

If the fuel consists of plutonium and depleted uranium (e.g. the fuel discharged from the reactor R-1), at a definite concentration of uranium-235 such fuel can be used practically without plutonium consumption. In this case all the fission fragments will be obtained as a result of fission of uranium-235 and plutonium formed in the reactor. The plutonium loaded together with fuel into the reactor, will act as a catalyzer. The burnup depth of this fuel will but slightly differ from that of natural uranium in uranium heavy-water converter reactors.

Conclusion

The experimental and theoretical studies on natural uranium heavy-water moderated organic cooled reactors, which were carried on for a number of years in the Institute of Experimental and Theoretical Physics (the results of which are presented in this report) lead us to a following conclusion upon potential uses of reactors of this type in nuclear power engineering:

1. Reactors of this type can be efficiently used as converters both for power generation and production of secondary nuclear fuel for fast breeders.

2. Reactors use natural uranium not previously enriched. High degrees of fuel burnup (up to 10000 MWd/t) and the possibility of using secondary fuel (plutonium) in the same reactors provide a favourable prospect for

constructing such reactors in countries which do not produce much uranium and do not have a sufficient quantity of fuel enriching factories.

3. The utilization of secondary nuclear fuel in the above reactors (which can be obtained as a result of natural uranium reprocessing in the same reactors) permits effectively using depleted uranium for nuclear power generation.

4. Organic-cooled reactors are the most reliable from the point of view of radiation safety as compared with the other known reactor types. Organic liquids fo not practically interact with uranium, which considerably decreases an opportunity for fission products to get into the first circuit with the fuel element cladding broken. It suggests an idea that organic-cooled reactors can be built near residential areas and used also as nuclear heating plants.

5. Rather high organic coolant thermal parameters reached at a small pressure facilitate constructing high power reactors (500 - 1000 MW).

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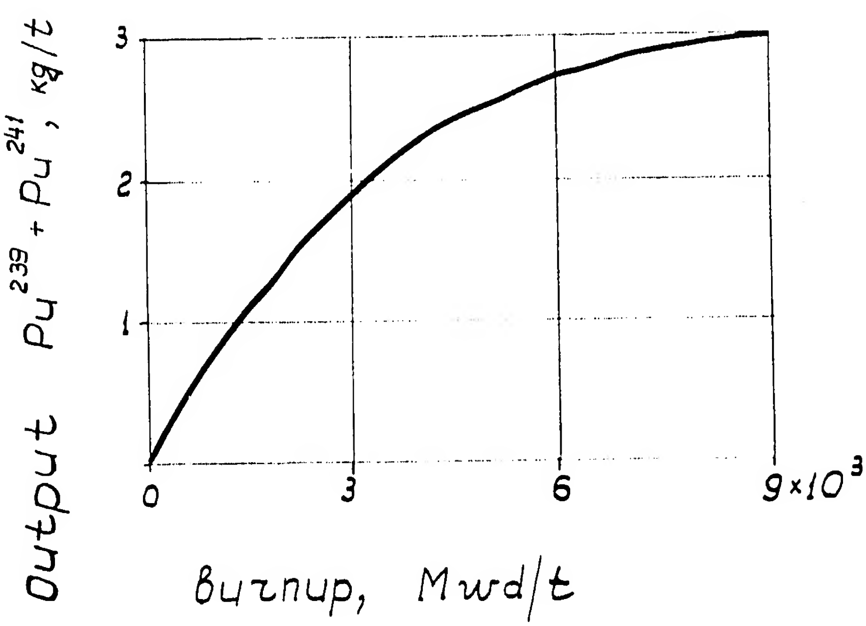

Fig. 1

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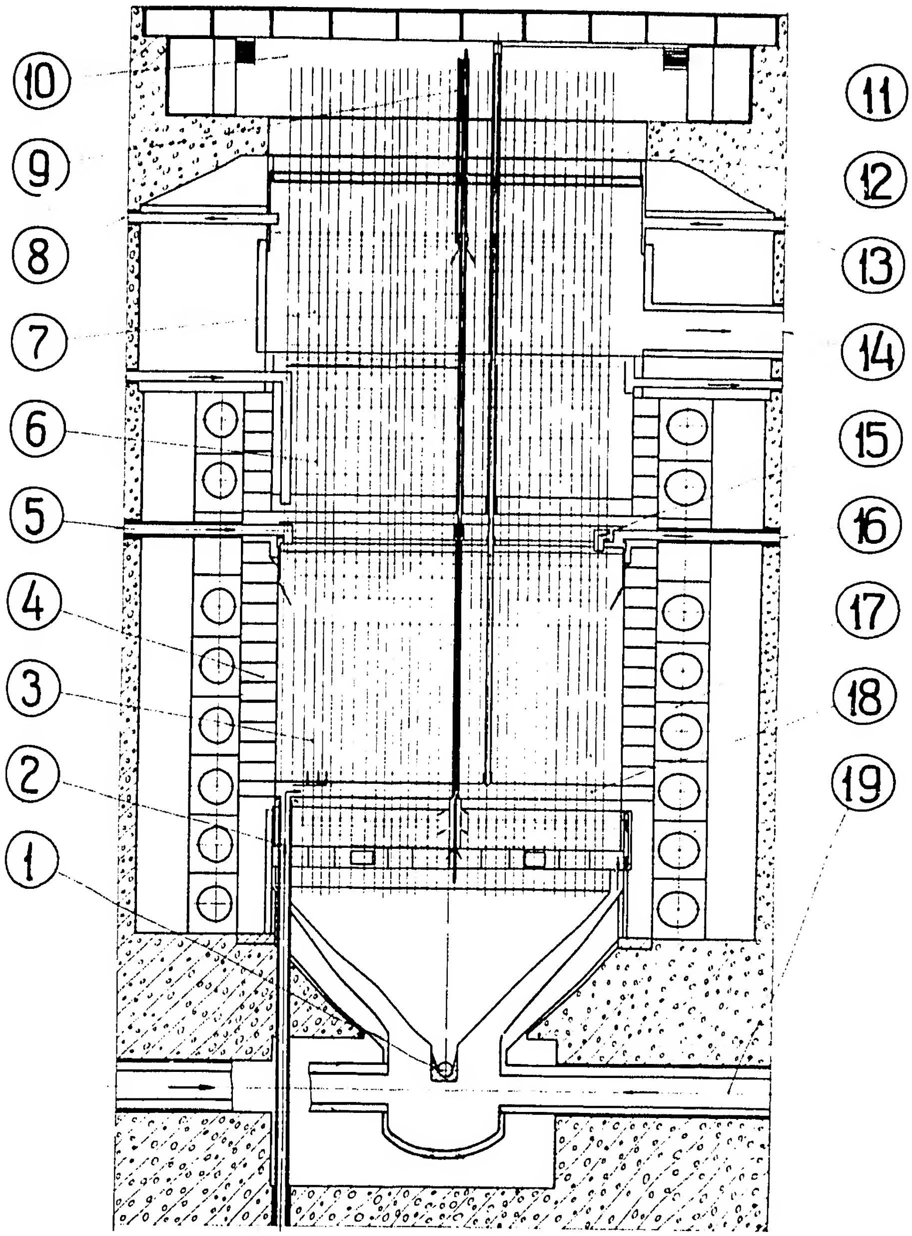

Fig. 2

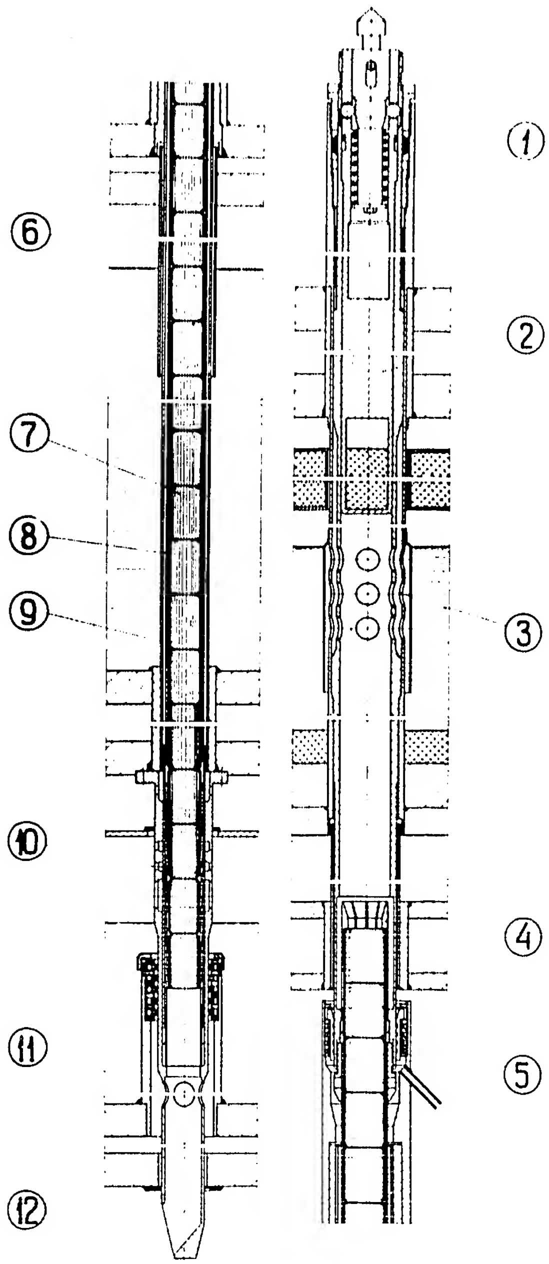

Fig. 3

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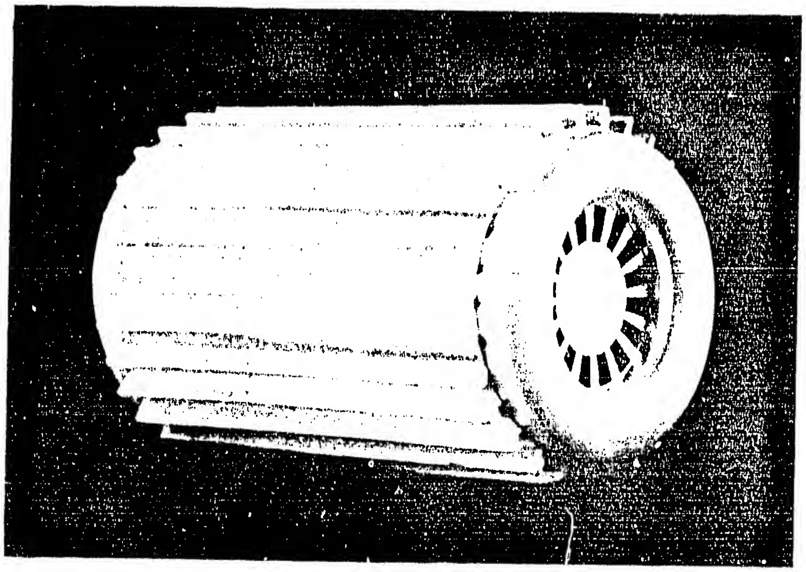

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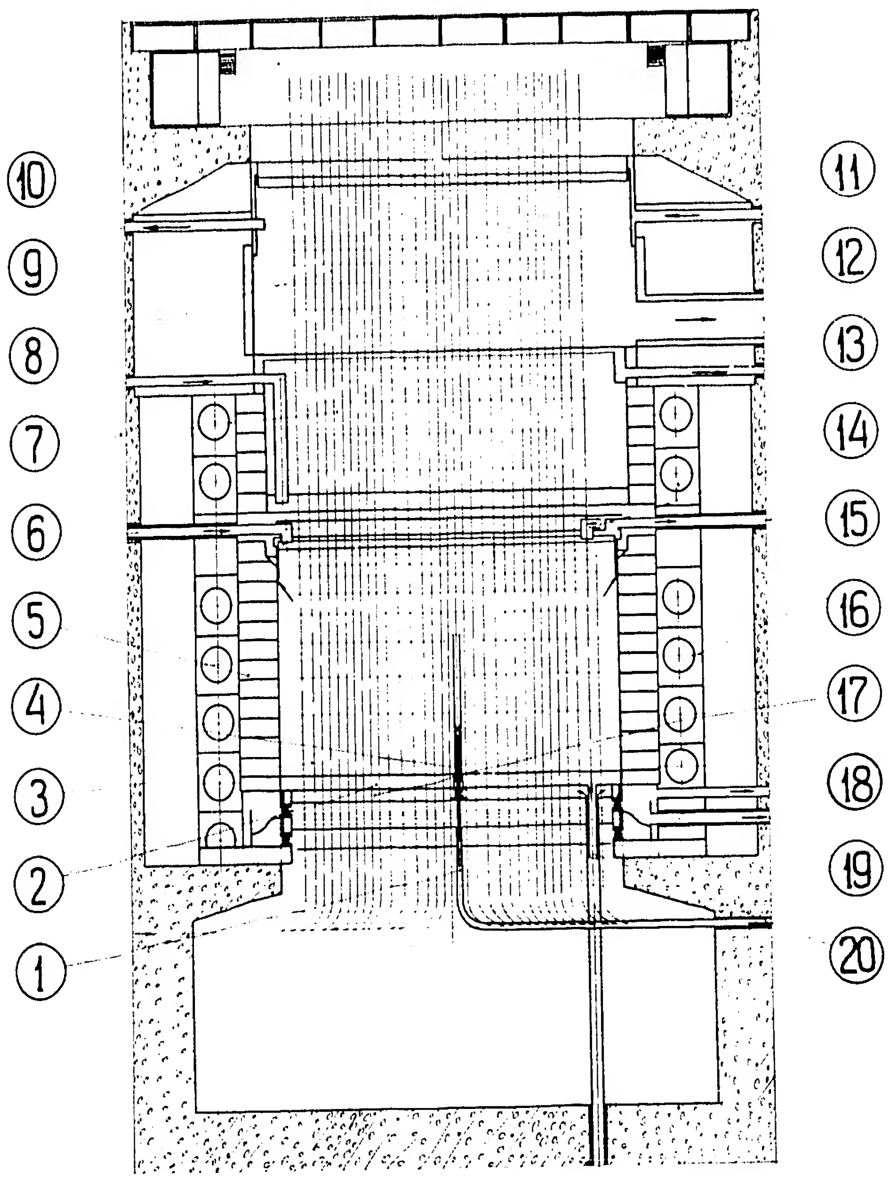

Fig. 5

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Captions

Fig.1. Pu^{239} and Pu^{241} accumulation versus burnup

Fig.2. R-1 reactor longitudinal cross-section.
1 - fuel elements trasportation system; 2 - moderator supply; 3 - core; 4 - graphite reflector; 5 - nitrogen supply for oxyhydrogen gas removal; 6 - shield tank ; 7 - dump tank ; 8 - nitrogen removal ; 9 - fuel channel; 10 - reactor top ; 11 - control and safety elements drive; 12 - conrol and safety elements channel; 13 - nitrogen supply for blowing off gaseous products resulting from coolant radiolysis ; 14 - coolant removal;15- nitrogen removal ; 16 - moderator removal; 17 - water shield; 18 - moderator supply collector ; 19 - coolant supply

Fig.3. Fuel channel of central zone.
1 - fuel channel front section; 2 - shield plug ; 3 - coolant drain; 4 - upper collet; 5 - throttle sealing; 6 - mouthpiece; 7 - fuel element; 8 - process tube; 9 - calandria-type tube; 10 - lower collet ; 11 - coolant supply; 12 - fuel channel rear section

Fig.4. Fuel element

Fig.5. R-2 reactor longitudinal cross-section .
1 - individual supply of coolant to fuel channels; 2 - moderator supply collector;3 - core; 4 - fuel channel; 5 - graphite reflector; 6 - nitrogen supply for blowing off oxyhydrogen gas; 7 - upper shield tank; 8 - dump tank; 9 - removal of gaseous products resulting from coolant radiolysis; 10 - reactor top; 11 - control and safety elements drive ; 12 - nitrogen supply; 13 - nitrogen removal ; 14 - removal of oxyhydrogen gas with nitrogen; 15 - moderator removal; 16 - water shield ; 17 - collector of nitrogen supply to moisture warning device; 18 - nitrogen removal with coolant radiolysis products ; 19 - coolant drain ; 20 - moderator supply